PARALLEL IMAGING FOR BODY MRI: CLINICAL PERSPECTIVE

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INTRODUCTION

Image acquisition speed is a crucial consideration for body applications of MRI. Minimizing the duration of breath holds is a universal goal of optimized thoracic and abdominal MR imaging. Shorter acquisitions allow for newer approaches towards contrast administration with the prospect that tighter bolus administrations may yield improved detection and characterization of pathologies. The fastest imaging sequences with current state-of-the-art scanners are approaching certain basic limits on imaging speed, related to the maximum switching rates of magnetic field gradients and radiofrequency (RF) pulses. Parallel imaging strategies represent an important next phase in accelerating image acquisitions. Trade-offs between acquisition times and resolution are being investigated. Parallel imaging, can be also be useful in optimizing the image quality from certain pulse sequences, particularly single shot approaches.

PRINCIPLES

Fast MR scanning is based on the optimization of the strengths, the switching rates, and the patterns of applied gradients and pulses. MR scanners can induce neuromuscular stimulation in the patient when field gradients are rapidly switched. Furthermore, excessively dense RF pulse trains can lead to unacceptable levels of RF energy deposition and heating of tissue.

Traditional fast imaging sequences have in common that imaging data is acquired in a sequential fashion. The MR signal is always acquired one point and one line at a time, with each separate line of data requiring a separate application of field gradients and/or RF pulses. Until recently, the speed of fast acquisitions has been limited by the maximum switching rates compatible with scanner technology and patient safety.

With the introduction of parallel MR imaging, imaging speeds have been increased beyond these limits. The term "parallel MRI" may be used to describe any magnetic resonance imaging strategy in which multiple MR signal data points are acquired simultaneously, rather than one after the other. Parallel imaging requires the use of coils with multiple detectors. Each of these detectors provides some component of distinct spatial information to the image.

Parallel imaging techniques exploit spatial information inherent in the geometry of a surface coil array. This information is used as a substitute for spatial modulations normally produced by phase encoding gradients. In so doing, multiple spatially encoded data sets (or multiple lines in *k*-space) are generated simultaneously for each application of a phase encoding gradient. Since phase encoding gradient application represents the time-consuming step in most sequential MRI techniques, parallel imaging techniques can significantly accelerate acquisitions of existing sequential fast imaging methods. Increase in imaging speed can be achieved without increasing gradient switching rate or RF power deposition.

An array of RF coils contains spatial information in the form of its component coil sensitivities. Composite sensitivity profiles can be generated by forming appropriate linear combinations of component coil signals. These sensitivity profiles oscillate in much the same way as the gradient-induced modulations. When a coil array with multiple elements is used, multiple harmonics may be generated from a single data set. These harmonics can be used to reconstruct multiple phase encoding lines in k-space reducing the number of phase encoding lines that are acquired during the scan time. One reconstruction method used in parallel imaging is known as simultaneous acquisition of spatial harmonics (SMASH) (1). Acquisition times are reduced by a factor that equals the number of harmonics that were generated. In other words, if a total of M spatial harmonics are generated, then M lines of k-space may be reconstructed for each application of a phase encoding gradient, and the total scan time will be a fraction $1/M$ of the usual acquisition time. The maximum achievable SMASH acceleration factor M is equal to the number of independent component coils in the array used for imaging. Therefore, the maximum speed is limited by the number of receiver channels in the imaging system.

A calibration of the RF sensitivities should be obtained before imaging acquisition is performed with parallel imaging techniques. This can be achieved from homogeneous phantoms or with in vivo calibration techniques. Fast reference images can be obtained that allow for in vivo calibration when flexible coils are used. Alternatively, auto-calibration techniques provide sensitivity profiles of the array coil at the time of data acquisition by adding a small number of reference k-space line that are then compared to the usual MR signal.

CLINICAL APLICATIONS

REDUCTION IN BREATH-HOLD

In a recent study we assessed the impact of parallel imaging using the VIBE sequence (2, 3). Three radiologists used a five-point scale to independently assign a score to these images for eight semi-quantitative metrics of image quality. As expected from theory, acceleration resulted in a reduction in average image quality with non-accelerated images receiving a significantly higher ($P<0.05$) average score of 3.8±0.3 (good), vs. 3.0±0.3 (acceptable) for the accelerated images. However, for patients that could not maintain a breath-hold for the duration necessary for non-accelerated imaging, reduced breathing artifact in the accelerated images resulted in improved image quality relative to the non-accelerated images.

IMPROVEMENT IN SPATIAL RESOLUTION

Parallel imaging techniques allow for increased spatial resolution in a given imaging time. This is particularly beneficial in breath-hold imaging when the available time is limited. Patients with limited breath-hold capacity can be scanned using standard breath-hold protocols by incorporating parallel imaging strategies.

Single-shot sequences particularly benefit from parallel imaging techniques (4). Reduction in the imaging time when using single-shot sequences leads to earlier acquisition of high spatial frequencies in k-space, with the subsequent reduced relaxation, and hence reduced attenuation. Parallel imaging allows for both reduced acquisition time and increased spatial resolution when single-shot sequences are used.

IMPROVEMENT IN TEMPORAL RESOLUTION

Increased temporal resolution is especially promising in cardiac MR imaging. Parallel imaging techniques have been used to achieve real-time cardiac images with temporal resolutions that exceed those of the 2D echocardiography without the use of view sharing. Also, reduction in the acquisition window at a fixed spatial resolution by virtue of an improved temporal resolution results in reduced motional blurring of the right coronary artery and other cardiac structures in accelerated images.

In another recent study the virtues of more rapid scanning were used to increase the sampling rate in the detection of hepatocellular carcinoma (5). In that study SENSE MRI with double arterial phase dynamic study showed higher sensitivity compared to the conventional technique. For HCCs $\leq$ 10 mm, the sensitivity and positive predictive values of parallel MRI were 78.6% and 78.6%, respectively, while those of conventional MRI were 27.3% and 60.0%, respectively. The number of detected HCCs $\leq$ 10 mm was significantly larger in parallel MRI than in conventional MRI ($P < 0.05$).

DECREASED TOTAL SCAN TIME IN LONG ACQUISITIONS

Reduction in overall duration of long acquisitions improves patient comfort and compliance. This has particular benefits for the pediatric patient population (6). The impact of reduction in total imaging time on patient throughput and cost-effectiveness of MR scanners still needs to be analyzed.

POTENTIAL PITFALLS AND ADVANCED TECHNIQUES:

Calibration of the spatial sensitivity patterns of array elements is a central step in any parallel imaging technique, and errors in calibration represent one of the most common and most pernicious sources of artifact in parallel MR images. Self-calibrating approaches (7, 8) which reduce or eliminate calibration errors are important for optimizing breath hold imaging. The accelerations associated with parallel imaging are generally associated with losses in signal-to-noise ratio. Tailored image reconstruction algorithms and coil array designs (9, 10) that minimize these losses can bestow further improvements to body imaging. New approaches to body imaging will employ accelerations in 2 dimensions to enhance 3D acquisitions and implement parallel imaging for spectroscopy (11, 12).

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